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TECHNICAL REPORT RD-GC-86-2

EVALUATION OF THE COLLINS/ROCKWELL TWO AXIS GYRO/ ACCELEROMETER SENSOR CLUSTER (PHASE III UNIT)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Phase III Two-Axis Gyro/Accelerometer (TAGA) cluster is a strapdown IMU with prelaunch self-calibration capabilities. The self-calibration mechanism allows for computer directed self tests which measure eight major performance parameters prior to launch. The purpose of this evaluation is to confirm performance stability of these eight parameters. The performance stability will decide the method of thermal compensation.

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I. INTRODUCTION

The Phase III two axis gyro/accelerometer (TAGA) sensor cluster differs from the Phase II cluster in that it has a prelaunch self-calibration mechanism. The self-calibration mechanism allows a computer directed self test which measures the following eight major performance parameters just prior to launch:

- Gyro scale factor
- Gyro drift bias
- Gyro misalignment about the spin axis
- On-axis G-sensitive drift
- Cross-axis G-sensitive drift
- Accelerometer scale factor
- Accelerometer bias
- Accelerometer misalignment about the spin axis

The primary purpose of the Phase III cluster evaluation is to determine the stability of the 958T-2 sensor. A stable sensor will allow for software polynominal thermal compensation, however, if the stability of the sensor is inadequate, a prelaunch self calibration may be required. For this reason, the 958T-2 sensor uncertainties are to be established to decide if software temperature calibration can be used in lieu of self-calibration mechanism.

II. DESCRIPTION OF THE SELF-CALIBRATION TAGA SENSOR CLUSTER

The self-calibration cluster consists of two TAGA sensors mounted at right angles as shown in Figure 1. Each sensor is mounted with its input axes A_i, B_i, and spin axis S_i.

Figure 1 shows the TAGA sensors in the navigation orientation with $\theta_{R1} = 0°$ and $\theta_{R2} = -90°$. Each sensor is capable of being rotated about an axis R_i nominally perpendicular to its spin axis S_i. Note that $\theta_{Ri} = 0°$, for each multisensor, results in A_i axes parallel to roll. The calibration process requires that measurements be made at three stationary orientations 90° apart, $\theta_{Ri} = 0°$, $-90°$ and $-180°$. In addition, displacement angle measurements are made as the sensors are rotated. The accumulated angles measured during the calibration rotations are used to determine gyro scale factor and gyro misalignment about the spin axis. All other parameters are calibrated from the stationary measurements, both gyros and accelerometers.

The calibration computation requires a computer. In addition to the computations, the calibration computer sends control commands to the torque motors in the cluster that cause the sensors to rotate about axes R_i. When the sensors are at data positions, they are locked to prevent motion. During rotation, the rate gyro pulses are used as velocity feedback to limit the speed of rotation. The gyro scale factor is determined from the total angle traveled between lock positions.

The accelerometer scale factor is calibrated to the local gravity. The calibration computer requires inputs of initial azimuth and latitude.

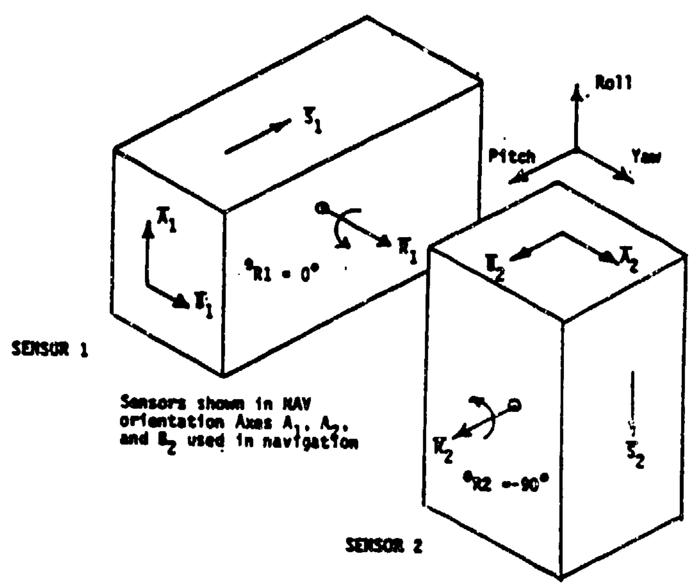

Figure 1. TAGA sensor axes and calibration rotation axes.

III. TAGA SENSOR CLUSTER TURN-ON/TURN-ON REPEATABILITY EVALUATION

A. General

The Phase III TAGA discussed in this report is a self-calibration instrument which is being evaluated for ground launched systems. The TAGA evaluation is based upon ambient self-calibration tests and special tests which include temperature exposure. The following is a description of the ambient test sequence in which the major performance parameters are measured:

- Energize TAGA sensors
- Wait 1 minute
- Start self-calibration cycle
- Collect and process data
- Wait 35 minutes
- Repeat self-calibration cycle
- Collect and process data
- Turn the TAGA sensors off
- Wait 4 hours and repeat test sequence

The results of the short-term ambient-test data depicting the eight performance parameters are shown in Tables 1 through 7.

B. Gyro Scale Factor

The 1σ turn-on to turn-on scale factor randomness of these gyros is summarized in Table 1. Each gyro scale factor is computer compensated for temperature sensitivity. The data was collected over a 4 day period. Scale factor data collected at time intervals of 1 minute and 35 minutes as described by the ambient test sequence are listed under gyro #1. The scale factor data collected at the same time intervals for gyro #2 are also tabulated in Table 1.

The variations of the scale factors summarized in Table 1 exhibit a spread of 795 to 798 PPM $\pm 1\sigma$ for gyro #2 and a spread of 1806 to 2006 PPM $\pm 1\sigma$ for gyro #1. These results indicate that the time dependent warm-up interval has minimal influence on the scale factor error.

TABLE 1. Gyro Scale Factor

	Gyro #1		Gyro #2	
Test #	1 Min, 25.0 °C	35 Min, 33.4 °C	1 Min, 26.4 °C	35 Min, 37.0 °C
1	.9970	.9945	1.0053	1.0031
2	.9957	.9948	1.0048	1.0012
3	.9970	.9975	1.0055	1.0022
4	.9954	.9990	1.0051	1.0035
5	.9985	.9972	1.0063	1.0035
6	.9986	.9940	1.0072	1.0020
7	.9992	.9978	1.0060	1.0028
8	.9934	.9967	1.0052	1.0026
$\bar{x}$	.9969	.9964	1.0057	1.0026
1σ	$\pm$.0020	$\pm$.0018	$\pm$.0008	$\pm$.0008

C. Gyro Bias Drift

The turn-on to turn-on bias repeatability was determined by using the ambient self-calibration test. The results are shown in Table 2. Each column shows bias data collected at indicated time intervals of 1 minute and 35 minutes for each axis (RA_1 and RB_1) of both gyros.

Gyro #1, 1 minute warm-up data, indicates that 68 percent of the bias data collected is within 1.1 °/hr. After a 35 minute warm up, gyro #1 exhibits a bias-drift rate of 2.1 °/hr. Gyro #2, 1 minute warm-up data, shows a bias drift of 2.3 °/hr; following a 35 minute warm-up period, gyro #2 exhibits a bias drift of 4.0 °/hr. These results imply that the turn-on to turn-on repeatability is not improved by allowing the instrument to reach thermal equilibrium.

TABLE 2. Gyro Drift Bias °/hr

Test #	Gyro #1				Gyro #2			
	RA_1		RB_1		RA_2		RB_2	
	1 Min	35 Min	1 Min	35 Min	1 Min	35 Min	1 Min	35 Min
1	2.6	7.0	-12.6	-12.7	9.3	8.2	0.9	8.4
2	2.4	6.2	- 9.1	-11.5	7.3	6.7	-1.7	12.5
3	2.7	5.3	- 9.8	-12.2	9.2	6.2	0.5	12.5
4	3.3	6.7	- 9.9	-13.1	10.5	7.9	-2.1	7.3
5	2.1	1.8	-10.1	-11.9	9.2	3.2	-0.1	3.8
6	1.2	3.1	-10.0	-11.6	11.7	11.7	-5.0	1.2
7	2.3	2.4	- 9.3	-10.7	9.9	9.4	-1.3	7.9
8	1.1	2.6	-10.4	-11.6	9.9	7.7	2.4	10.1
$\bar{x}$	2.2	4.4	-10.2	-11.9	9.6	7.6	-0.8	8.0
1σ	$\pm$0.8	$\pm$2.1	$\pm$ 1.1	$\pm$0.8	$\pm$1.3	$\pm$2.5	$\pm$2.3	$\pm$4.0

D. Gyro G-Sensitive Drift

The g-sensitive drift for each gyro was determined concurrently by using the ambient self-calibration test sequence. The results are given in Table 3. The data, tabulated in the caption columns, represent the g-sensitive on-axis (GSA) and cross-axis (GSB) drift rates. The standard deviation for axes RA_1 and RB_1 and the average temperature of each gyro are shown in the appropriate column.

The 1σ values in Table 3 are summarized. For a 1 minute warm-up period, Gyro #1 GSA drift rate is 2.8 °/hr/g; the GSB drift is 1.3 °/hr/g. After 35 minutes, the GSA drift is 3.5 °/hr/g; GSB drift is 1.4 °/hr/g. For Gyro #2, the 1 minute warm-up GSA drift is 2.6 °/hr/g; GSB drift is 1.6 °/hr/g. After a 35 minute warm up, the GSA drift is 4.2 °/hr/g; the GSB drift is 2.4 °/hr/g. These results confirm that a temperature-stabilized instrument is not required.

The mean drift data in Table 3 is temperature dependent. As a result, special tests were designed to calibrate the temperature sensitivity of the TAGA. The results of these special tests are discussed in section V.

TABLE 3. Gyro G-Sensitive Drift °/hr/g

Test #	Gyro #1 GSA 1 Min	Gyro #1 GSA 35 Min	Gyro #2 GSA 1 Min	Gyro #2 GSA 35 Min	Gyro #1 GSB 1 Min	Gyro #1 GSB 35 Min	Gyro #2 GSB 1 Min	Gyro #2 GSB 35 Min
1	21.0	-26.1	46.3	-5.1	36.3	55.1	-18.6	-10.4
2	27.8	-20.2	48.4	-4.0	35.4	53.2	-15.6	- 7.6
3	27.4	-15.6	51.1	0.3	35.2	51.3	-18.6	- 7.3
4	27.7	-16.9	45.7	0.4	34.9	51.8	-16.6	- 7.8
5	24.9	-18.1	50.2	6.7	37.9	52.2	-20.1	-13.8
6	27.0	-17.5	51.5	6.3	37.9	55.0	-16.0	-11.9
7	28.4	-19.1	51.2	0.3	36.6	53.0	-18.5	- 7.8
8	30.5	-15.1	52.8	2.6	37.8	53.9	-18.7	-10.4
$\bar{x}$	26.8	-18.6	49.6	0.9	36.5	53.2	-17.8	- 9.6
1σ	$\pm$2.8	$\pm$ 3.5	$\pm$2.6	$\pm$4.2	$\pm$1.3	$\pm$1.4	$\pm$ 1.6	$\pm$ 2.4
Temp°C	25.0$\pm$.4	33.4$\pm$.5	26.4$\pm$.5	37.0$\pm$.5	—	—	—	—

GSA On-axis g-sensitive drift
GSB Cross-axis g-sensitive drift

E. Gyro Misalignment About the Spin Axis

The multifunction gyro requires that sinusoidal signals be demodulated to yield two axes of measurement data. A "reference mark," on the gyro wheel, is used to synchronize the demodulator with the wheel position. Errors in the reference mark will cause an apparent misalignment error about the spin axis. Other electronic errors in the signal channels can also cause apparent misalignment errors.

Data from the ambient self-calibration tests are used to calibrate alignment about the spin axis. The results are shown in Table 4. It indicates that the maximum standard deviation of misalignment about the spin axis for Gyro #1 is 1.4 mrad and for Gyro #2 is 0.7 mrads.

TABLE 4. Gyro Misalignment Angle About the Spin Axis (mrad)

Test #	Gyro #1		Gyro #2	
	1 Min	35 Min	1 Min	35 Min
1	4.3	3.3	8.0	6.0
2	5.2	1.6	8.2	8.5
3	5.5	1.6	7.7	7.9
4	3.4	2.1	8.4	7.2
5	3.4	1.5	8.0	7.4
6	4.2	1.5	7.7	7.6
7	0.9	0.6	7.6	8.1
8	3.6	1.4	7.5	7.4
$\bar{x}$	3.8	1.7	7.9	7.5
1σ	± 1.4	± 0.8	± 0.3	± 0.7

F. Accelerometer Scale Factor

The turn-on to turn-on accelerometer scale factor repeatability data are listed in Table 5. This data was collected over a 4 day period concurrently with the gyro ambient self-calibration test-gyro data.

The standard deviation of the scale factors exhibits a spread of 399 to 798 PPM for accelerometer #1 and from 300 to 401 PPM for accelerator #2.

TABLE 5. Accelerometer Scale Factor

Test #	Accelerometer 1		Accelerometer 2	
	1 Min	35 Min	1 Min	35 Min
1	1.0028	1.0025	0.9999	0.9979
2	1.0020	1.0017	0.9991	0.9971
3	1.0020	1.0015	0.9998	0.9980
4	1.0025	1.0024	0.9994	0.9982
5	1.0021	1.0015	1.0002	0.9986
6	1.0021	1.0022	0.9994	0.9981
7	1.0024	1.0016	0.9995	0.9982
8	1.0026	1.0017	0.9996	0.9982
$\bar{x}$	1.0021	1.0019	0.9996	0.9980
1σ	$\pm$.0008	$\pm$.0004	$\pm$.0003	$\pm$.0004

G. Accelerometer Bias

Accelerometer bias was calibrated for the Phase III self-calibration multifunction sensors. The results, over 4 days of tests, are shown in Table 6. The standard deviations of the accelerometer bias for all axes are between 300 to 700 μg.

TABLE 6. Accelerometer Bias (mg)

Test #	AA_1		AB_1		AA_2		AB_2	
	1 Min	35 Min	1 Min	35 Min	1 Min	35 Min	1 Min	35 Min
1	.2	.0	11.1	11.6	5.9	5.5	-1.3	-0.9
2	-.5	-.3	12.2	10.6	7.5	6.1	-2.6	-0.4
3	-.4	-.4	12.3	11.0	6.6	5.6	-1.0	0.3
4	.1	.3	13.0	11.7	7.6	6.4	-2.2	-0.3
5	-.6	-.6	12.8	11.7	6.9	5.1	-0.9	0.3
6	-.2	.2	11.7	11.3	6.3	5.3	-1.6	-0.2
7	-.5	-.6	12.7	11.9	7.1	6.2	-2.5	-0.5
8	-.1	-.5	13.3	12.2	6.5	5.0	-1.3	-0.2
$\bar{x}$	-.25	-.24	12.4	11.5	6.8	5.6	-1.7	-0.2
1σ	$\pm$.30	$\pm$.36	$\pm$0.7	$\pm$0.5	$\pm$.6	$\pm$.5	$\pm$ .7	$\pm$0.4

H. Accelerometer Misalignment Angle About the Spin Axis

Data from the ambient self-calibration tests are used to calibrate alignment about the accelerometer spin axis. The data from these tests are shown in Table 7. As shown, the maximum standard deviation of misalignment about the spin axis for accelerometer #1 and accelerometer #2 is 0.5 mrads.

TABLE 7. Accelerometer Misalignment Angle About the Spin Axis (mrad)

	Accelerometer 1		Accelerometer 2	
Test #	1 Min	35 Min	1 Min	35 Min
1	−0.4	−0.7	9.8	8.5
2	−0.5	−0.4	10.2	9.6
3	−0.7	−0.4	10.5	9.3
4	−0.1	−0.3	10.6	9.5
5	−1.1	−1.0	10.3	9.3
6	−0.4	−0.3	10.0	9.0
7	−0.8	−0.6	10.2	10.0
8	−1.1	−1.8	10.3	9.7
$\bar{x}$	−0.6	−0.7	10.2	9.4
1σ	±0.4	±0.5	±0.3	±0.5

IV. COMPARISON OF THE SIX-POSITION VS SELF-CALIBRATION DATA

A. Six-position testing is a test routine where the instrument is mounted in a precision three-axes gimbal test stand. This enables the user to accurately rotate the unit to the appropriate test positions. The results of the six-position tests are shown in Table 8.

B. At the end of each six-position test, a self-calibration test was executed. The comparison results are tabulated in Table 8 parallel to the appropriate six-position test data.

C. The last column in Table 8 shows the difference between the six-position and self-calibration data. The gyro bias has a maximum spread of 2.8 °/hr. The g-sensitive correlation error is 8.1 °/hr/g; but this parameter is highly sensitive to temperature. For this reason, the change in temperature of each test (see Note in Table 8) must be considered when comparing the performance parameters.

D. The comparison data for the accelerometers are also shown in Table 8. The AB_2 bias difference is quite large, 4.14 mg; however, the bias differences for the other three axes seem to be reasonable.

Table 8. Six-Position Test Data vs Self-Calibration Data[1]

Parameters	Gyro Six-Position Data	Gyro Self-Calibration Data	Correlation Error
$RA_1(R_{AAV})$	9.3 °/hr	7.7 °/hr	1.6
$RB_1(R_{AAV})$	28.8 °/hr	31.6 °/hr	2.8
$RA_2(R_{SAV})$	9.2 °/hr	11.3 °/hr	2.1
$RB_2(R_{SAV})$	28.0 °/hr	25.3 °/hr	2.7
RA_1(GSA)	-60.6 °/hr/g	-68.7 °/hr/g	8.1
RA_1(GSB)	57.5 °/hr/g	60.2 °/hr/g	2.7
RA_2(GSA)	-22.2 °/hr/g	-27.8 °/hr/g	5.6
RA_2(GSB)	- 5.7 °/hr/g	- 7.1 °/hr/g	1.4
Parameters	**Accelerometer Six-Position Data**	**Accelerometer Self-Calibration Data**	**Correlation Error**
AA_1 Bias	- 0.56 mg	- 2.27 mg	1.71
AB_1 Bias	- 0.72 mg	0.08 mg	0.80
AA_2 Bias	3.99 mg	3.54 mg	0.45
AB_2 Bias	- 2.40 mg	- 6.54 mg	4.14

[1]NOTE

Gyro #1 start test Temp 36.3, stop test Temp 39.4 °C.
Gyro #2 start test Temp 38.1, stop test Temp 41.1 °C.

V. SELF-CALIBRATION TEMPERATURE TESTS

All self-calibration temperature tests were made with the instrument mounted in the navigation orientation. Three self-calibration tests were conducted at each temperature stable condition. The instrument was allowed to thermally restabilize for 45 minutes between each test. The same procedure was repeated at eight different temperature settings. Figures 2 through 21 summarize the results of these prelaunch calibration tests.

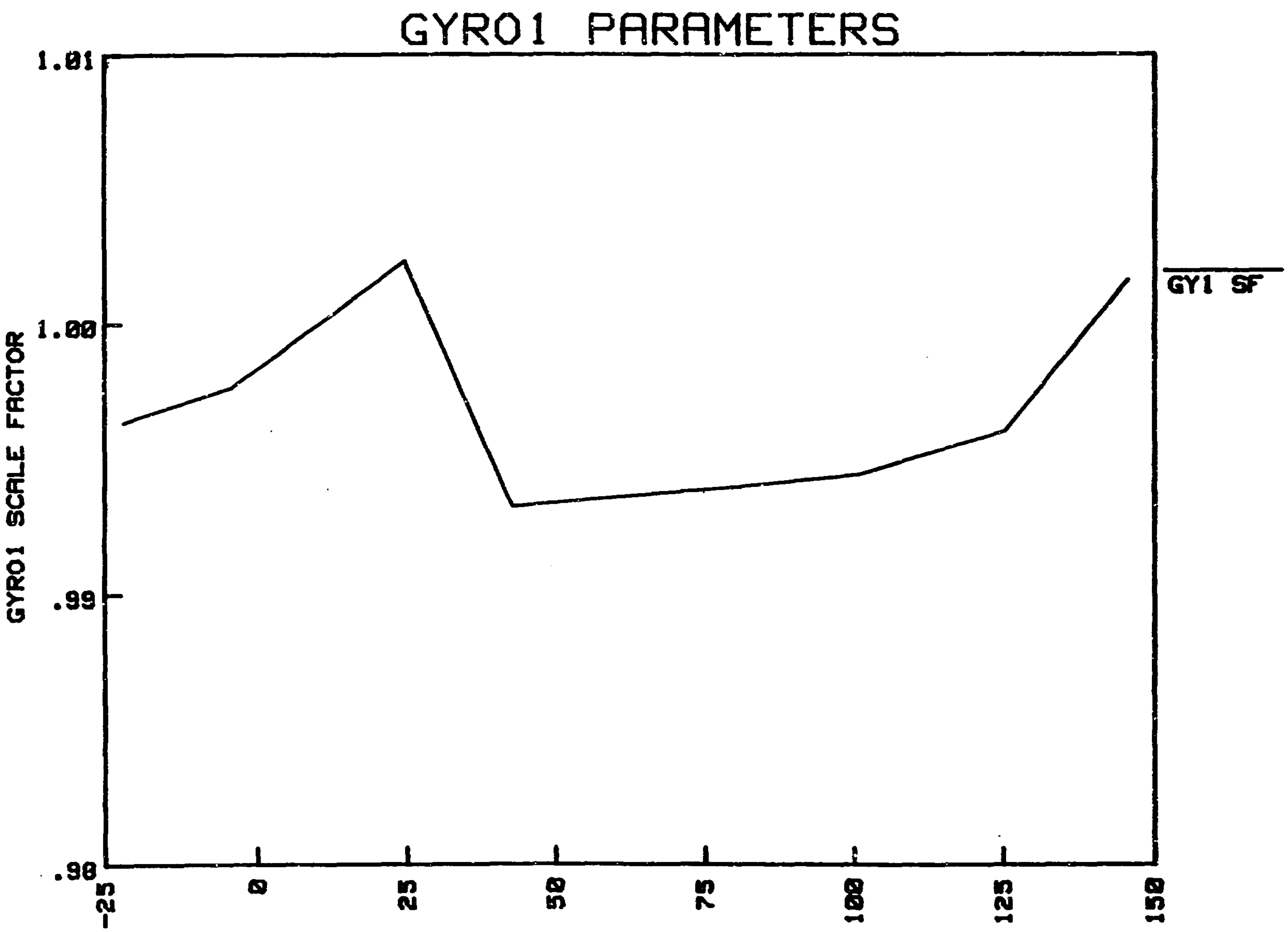

Figure 2. Gyro 1 scale factor/temperature.

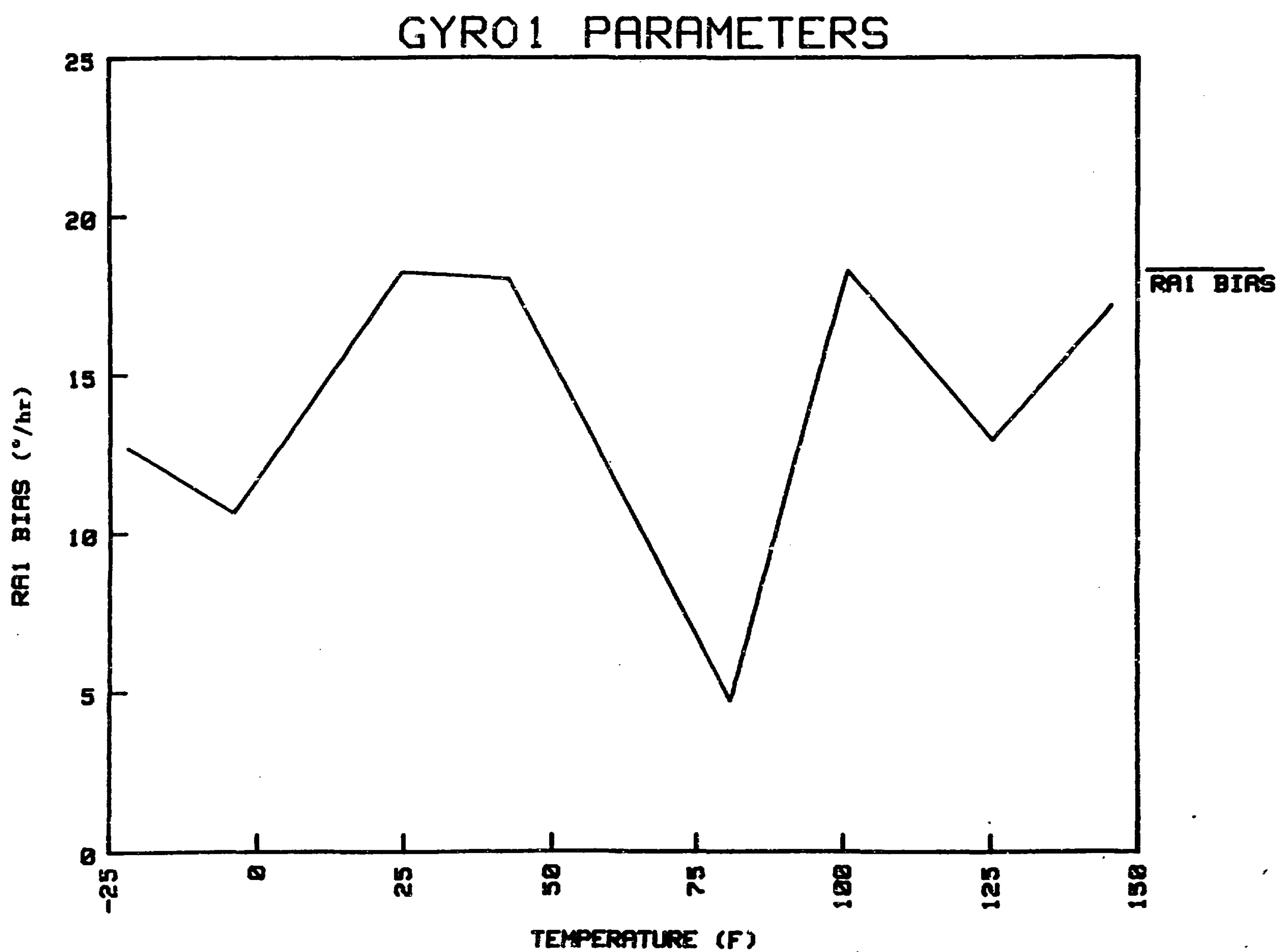

Figure 3. Gyro 1 bias drift/temperature (RA_1).

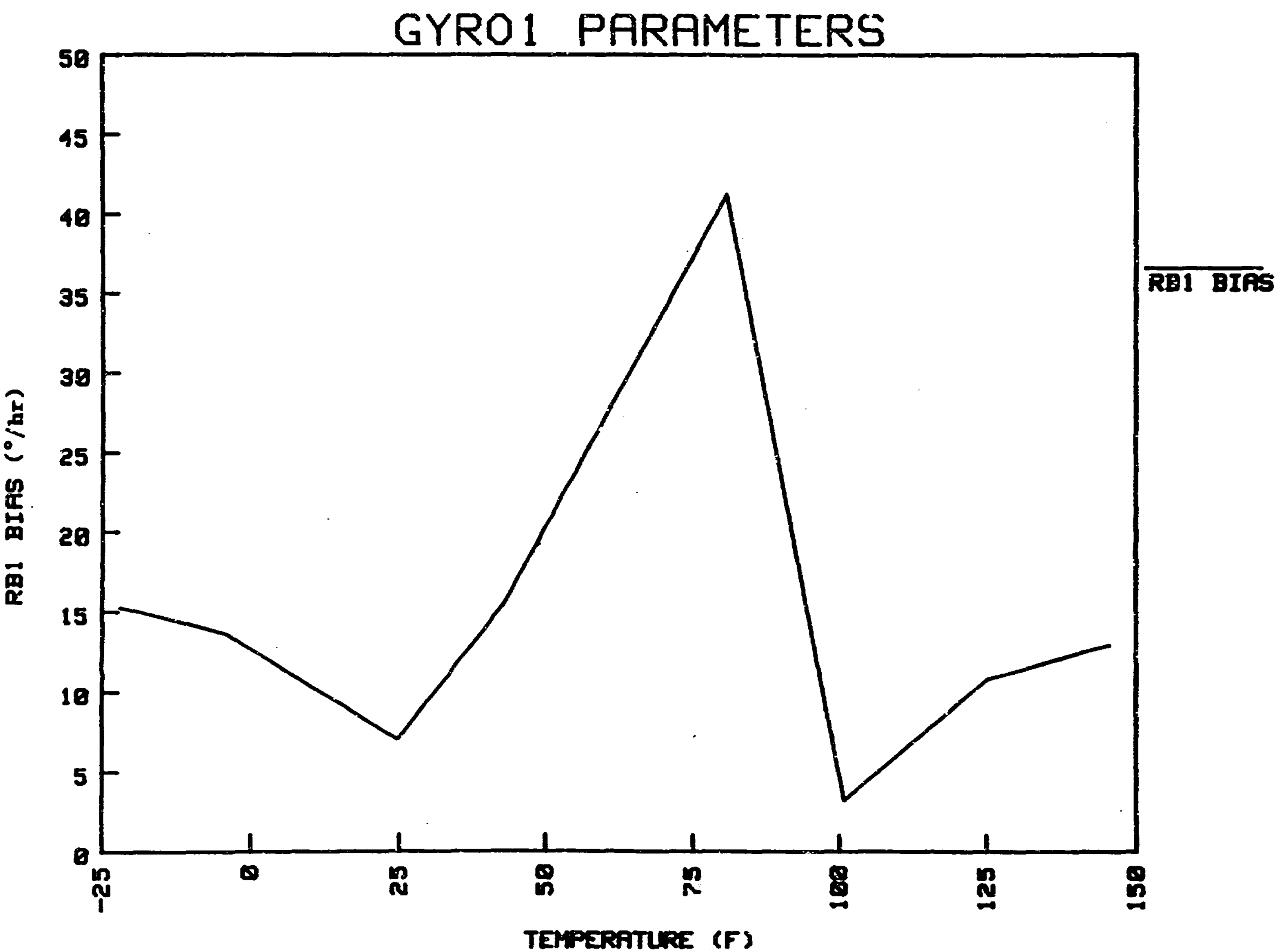

Figure 4. Gyro 1 bias drift/temperature (RB_1).

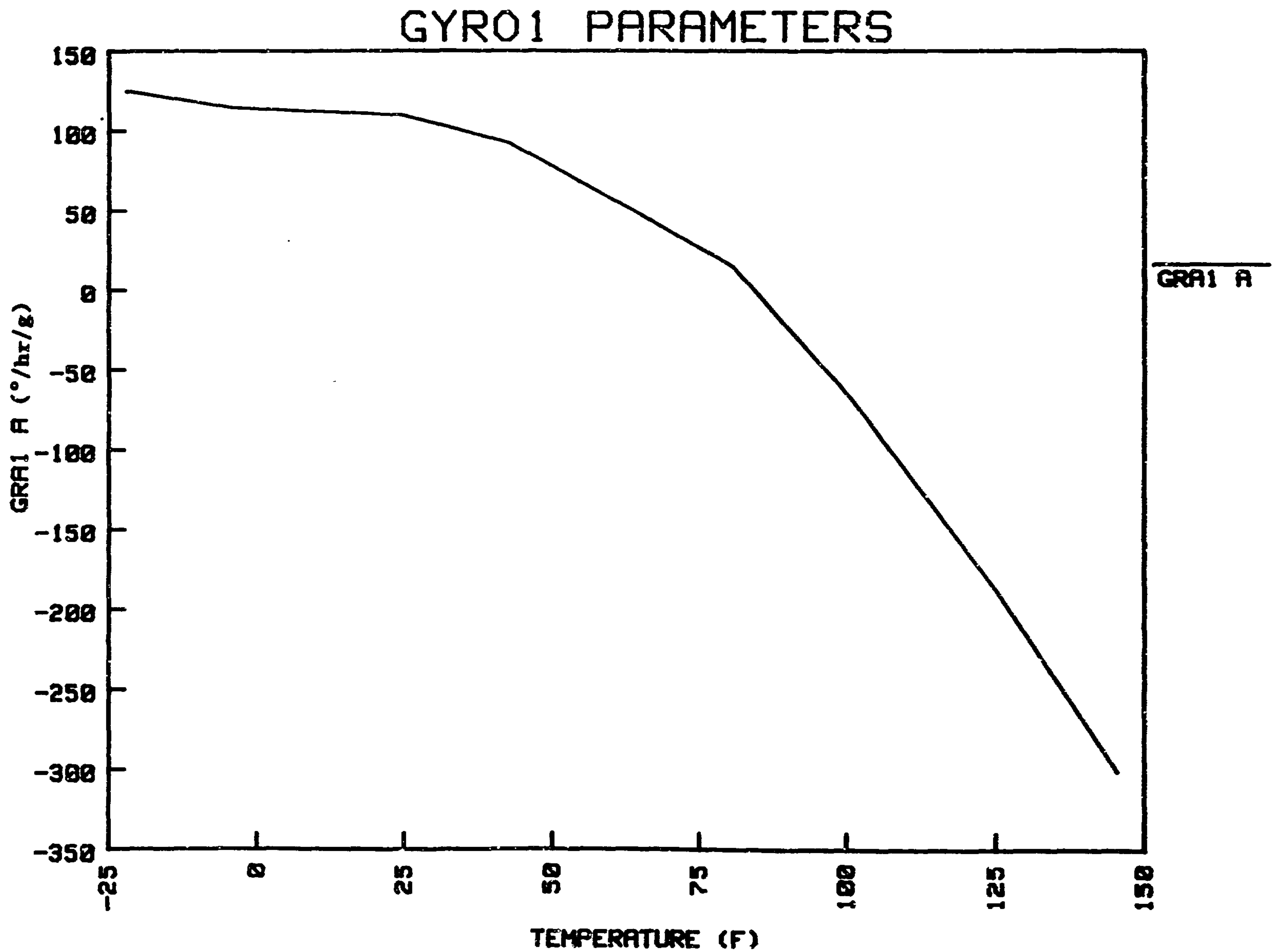

Figure 5. Gyro 1 g-sensitive drift/temperature (GRA1A).

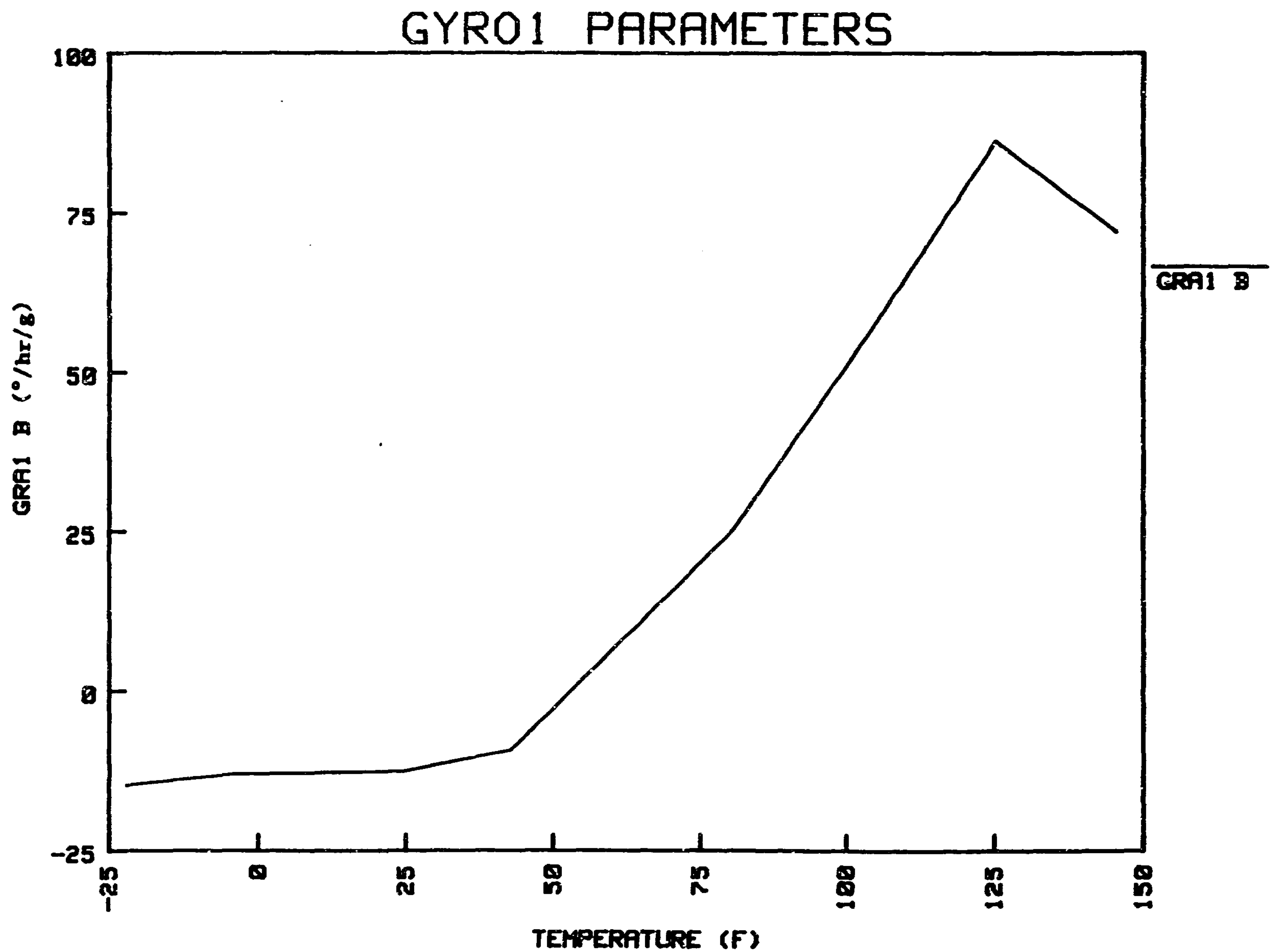

Figure 6. Gyro 1 g-sensitive drift/temperature (GRA1B).

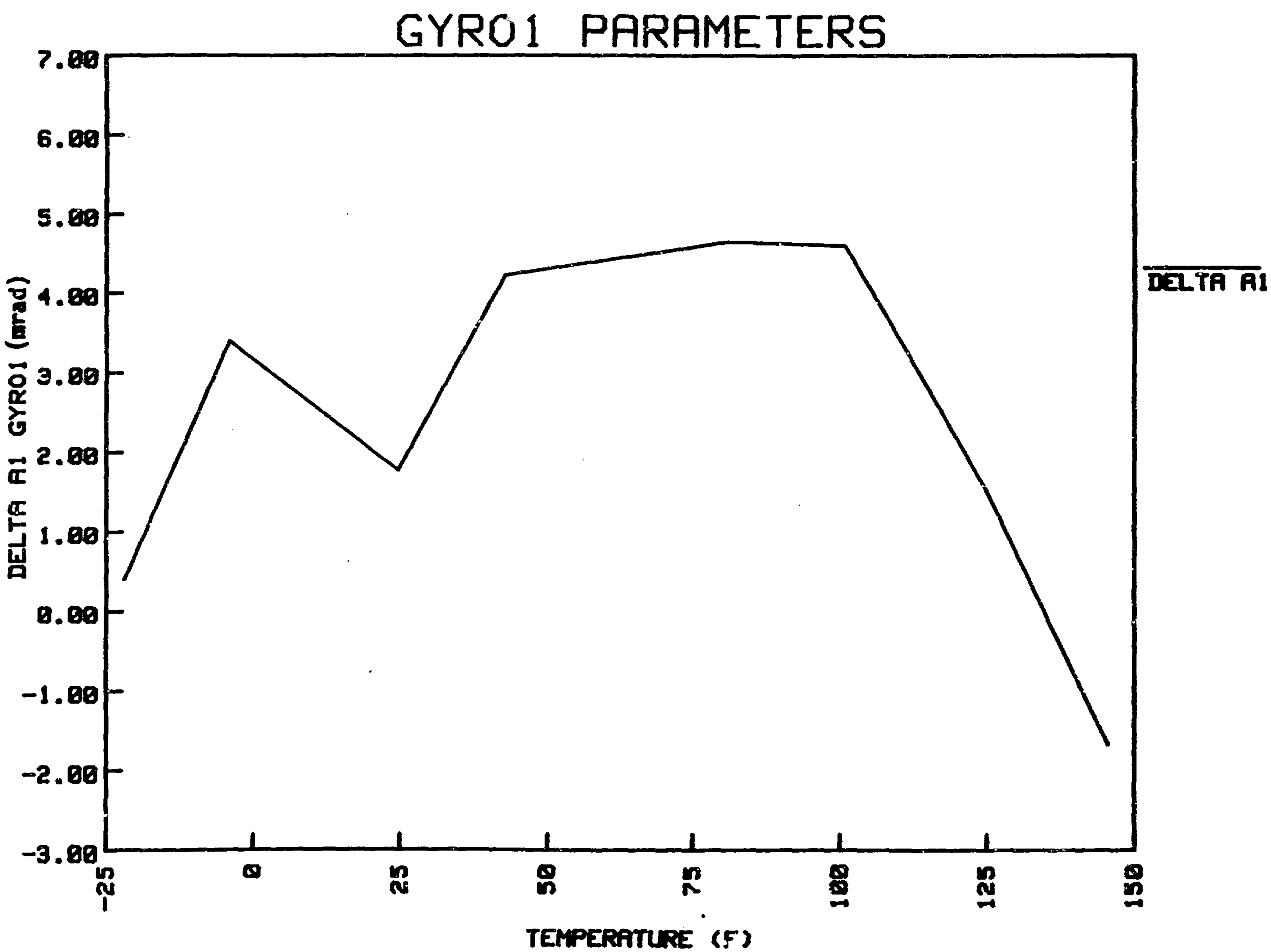

Figure 7. Gyro 1 misalignment error.

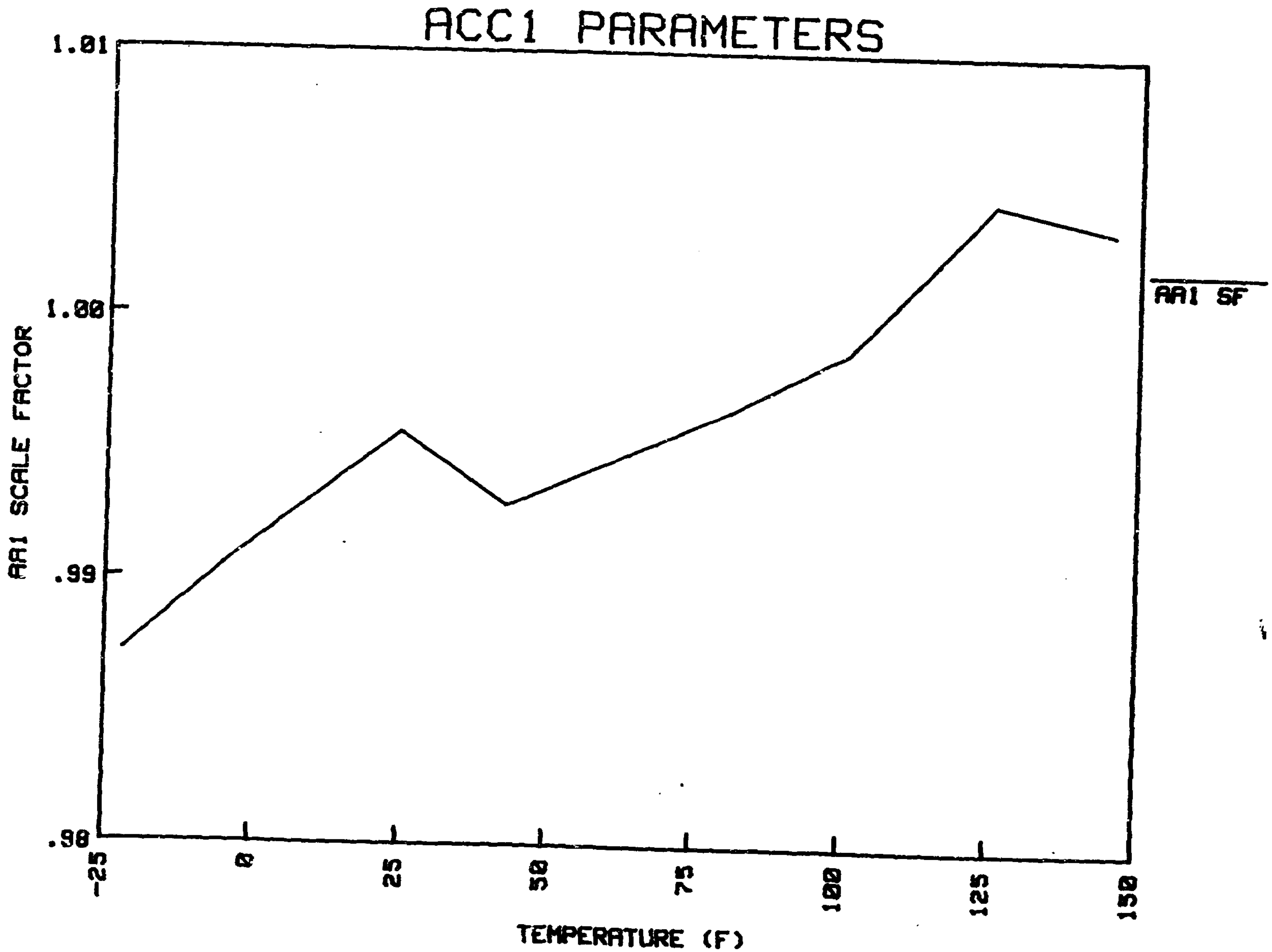

Figure 8. Accelerometer 1 scale factor/temperature.

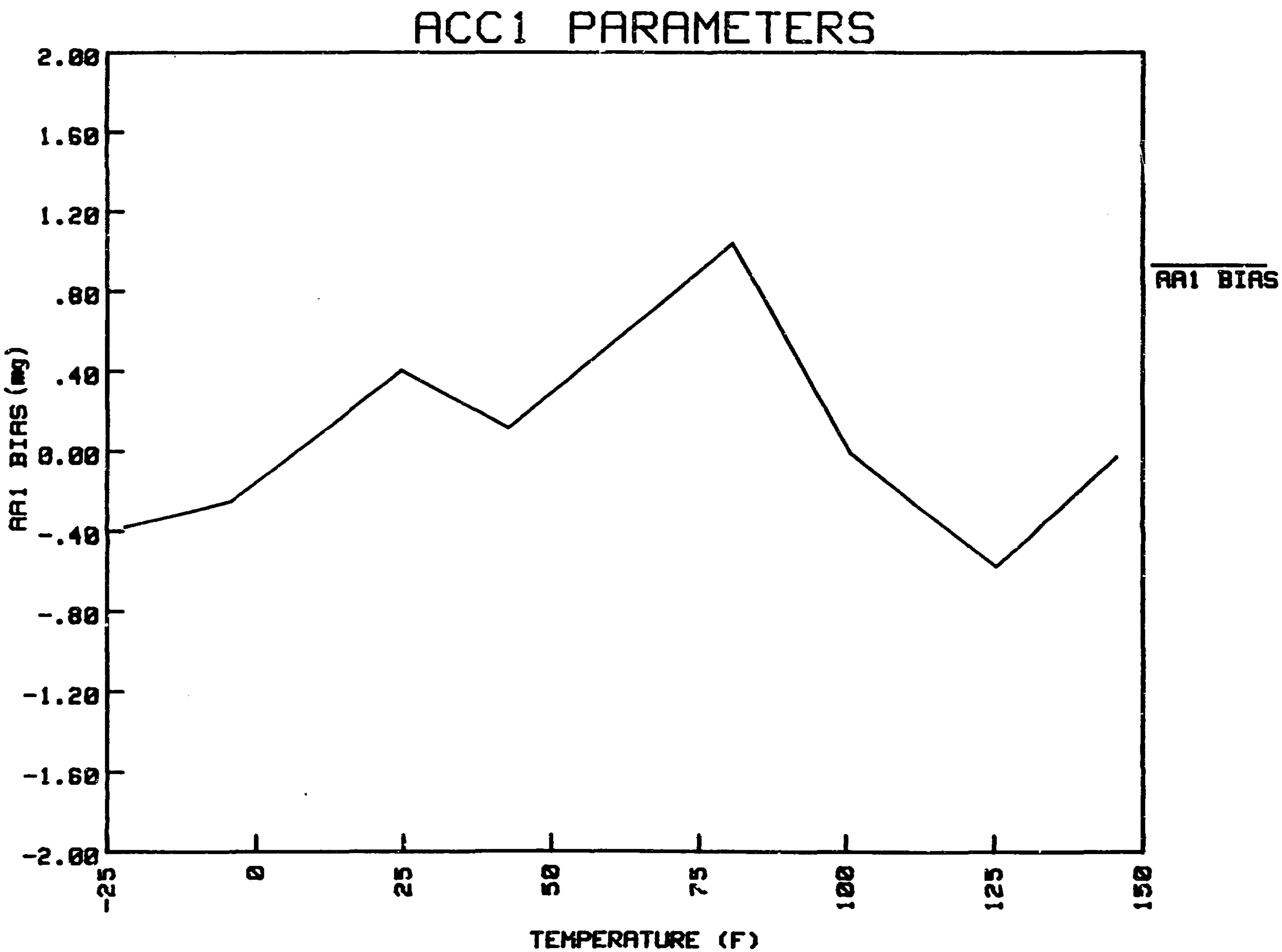

Figure 9. Accelerometer 1 bias/temperature (AA1).

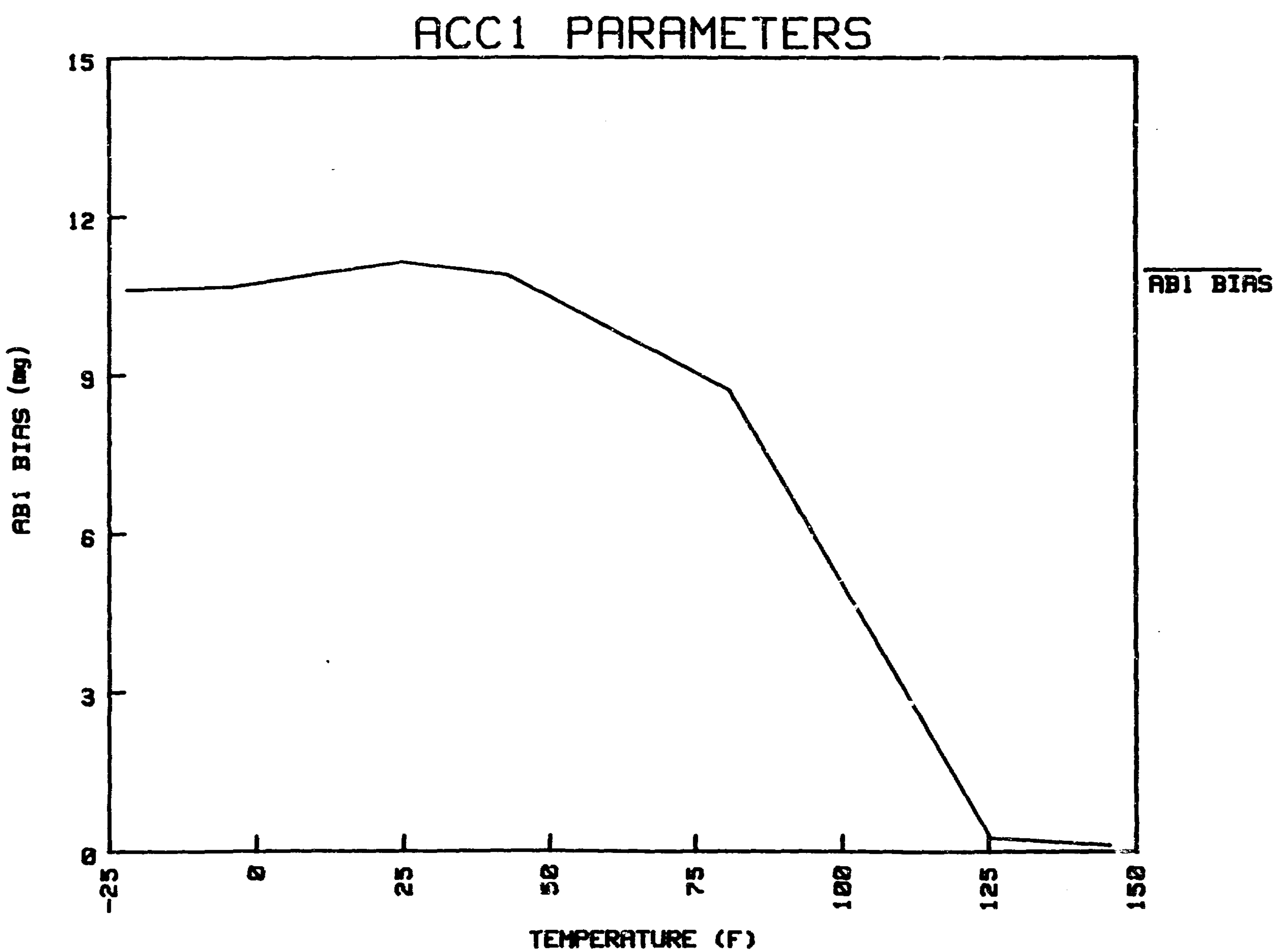

Figure 10. Accelerometer 1 bias/temperature (AB1).

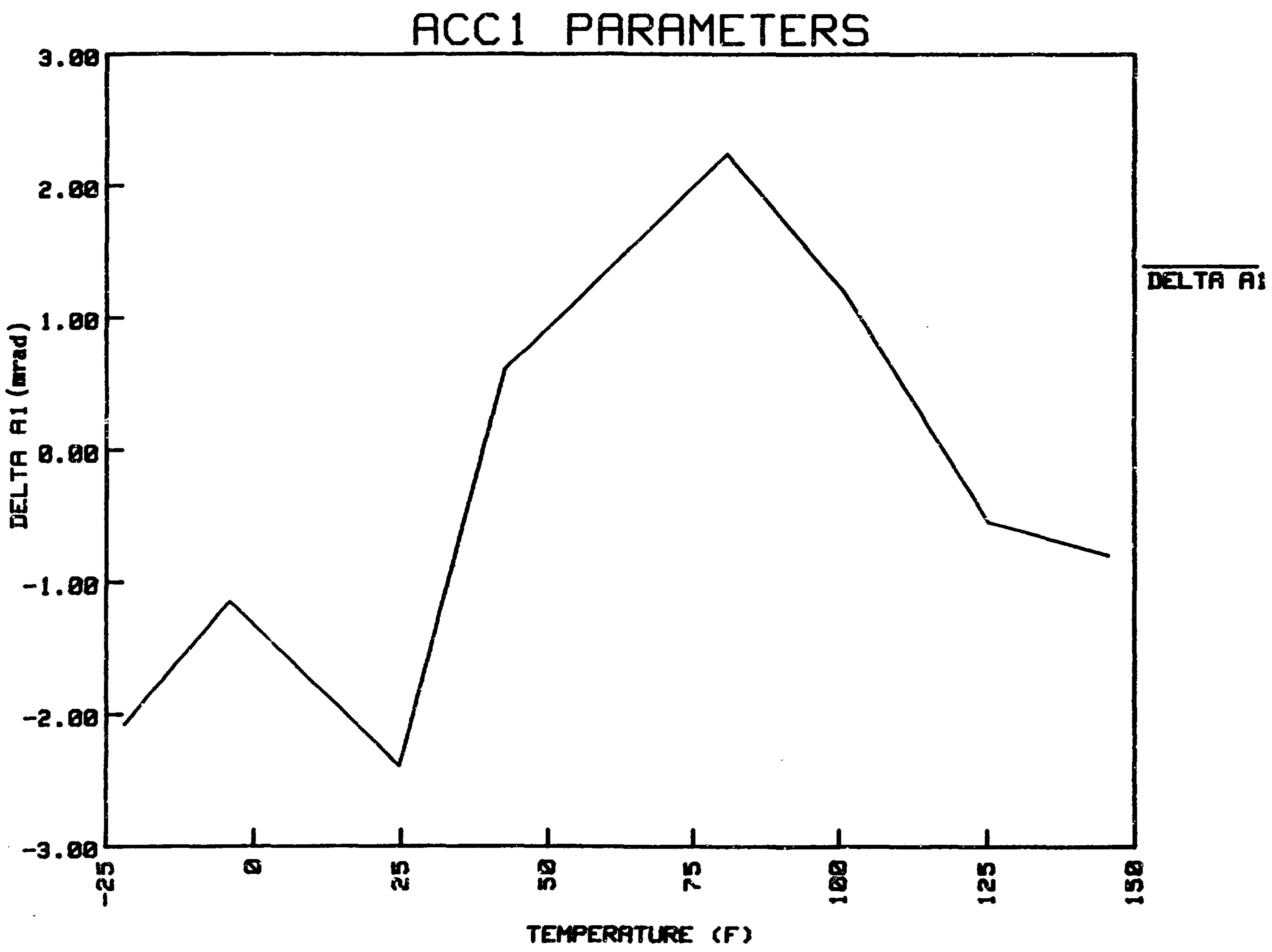

Figure 11. Accelerometer 1 misalignment error.

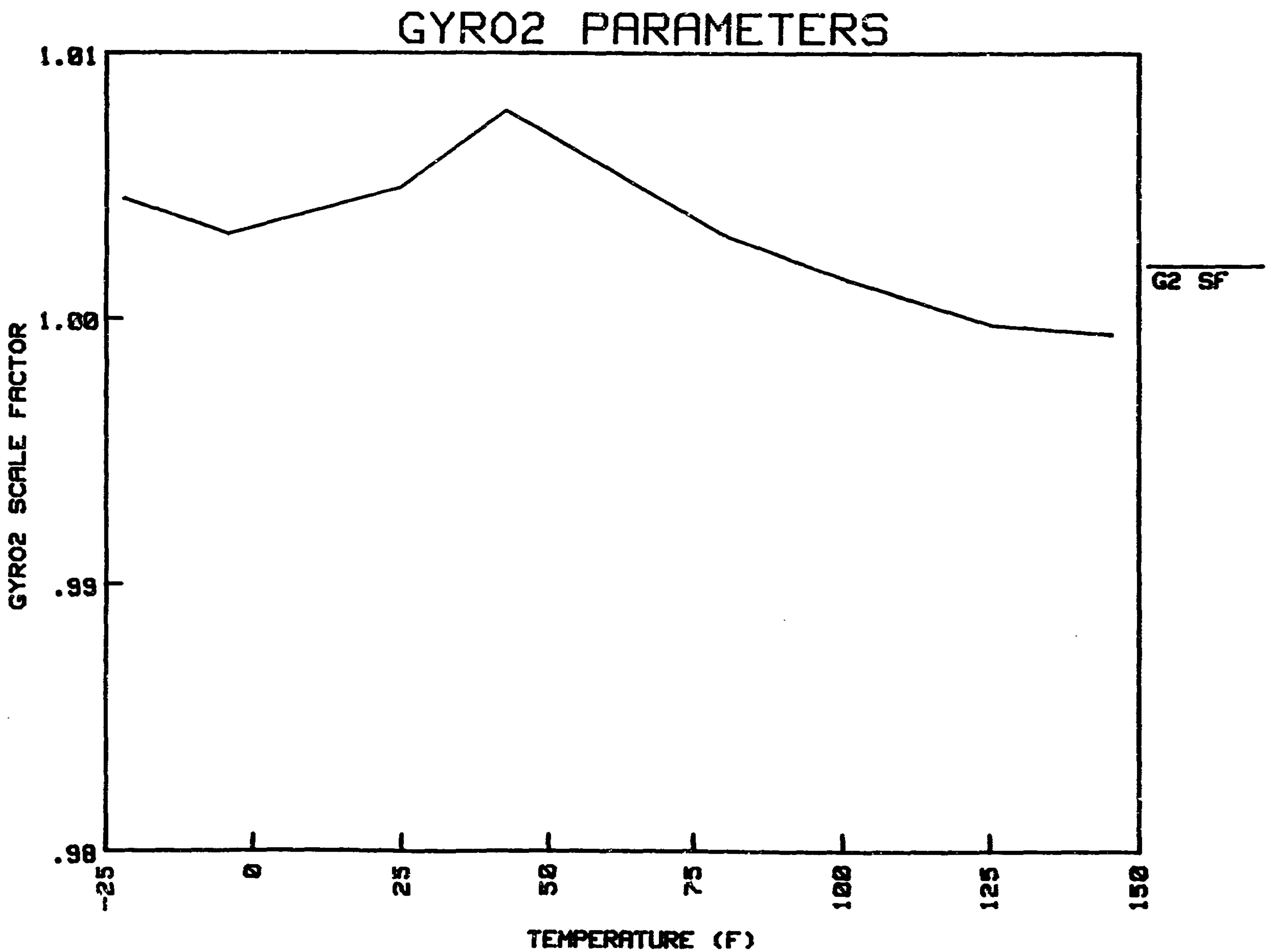

Figure 12. Gyro 2 scale factor/temperature.

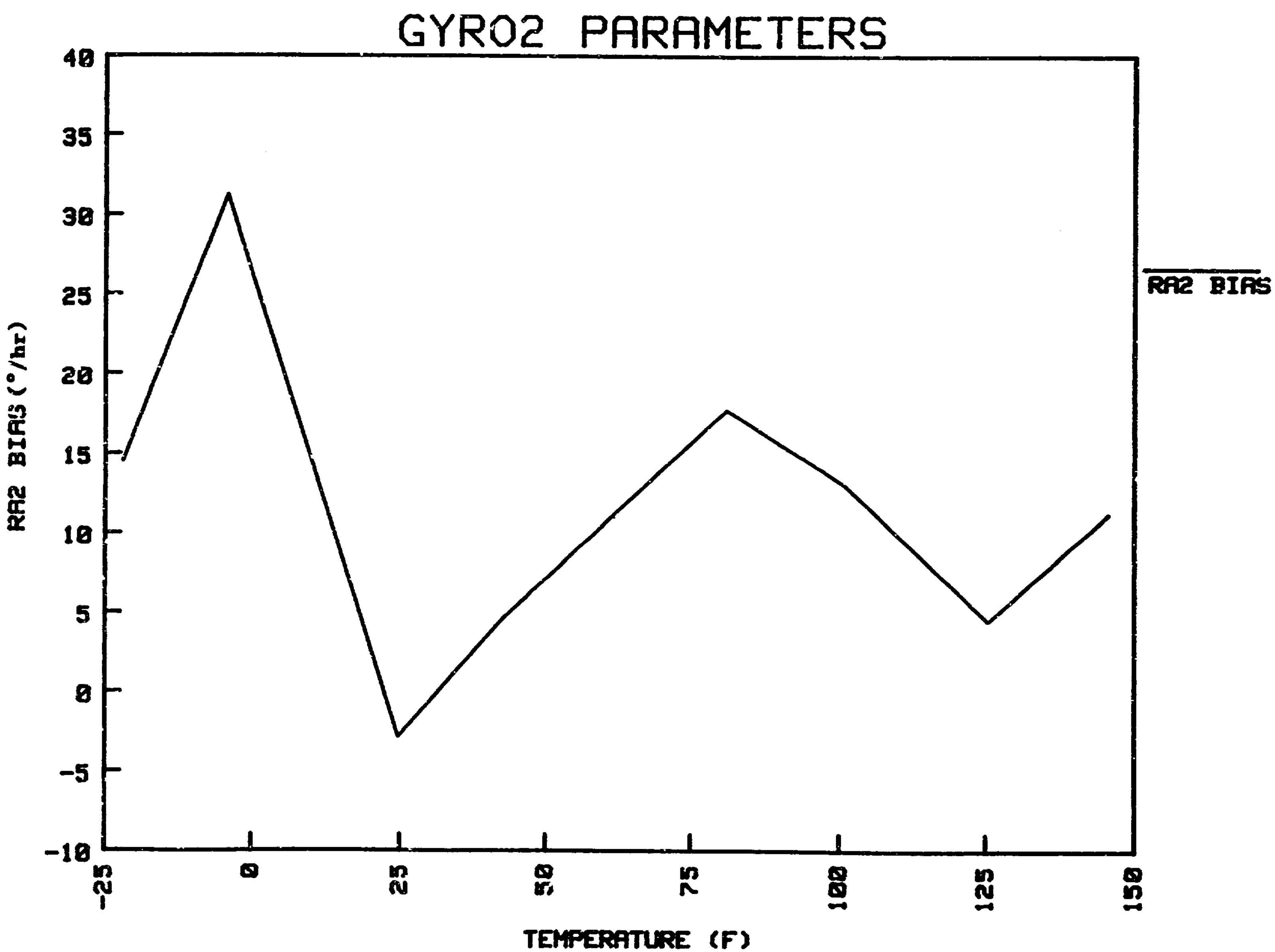

Figure 13. Gyro 2 bias drift/temperature (RA2).

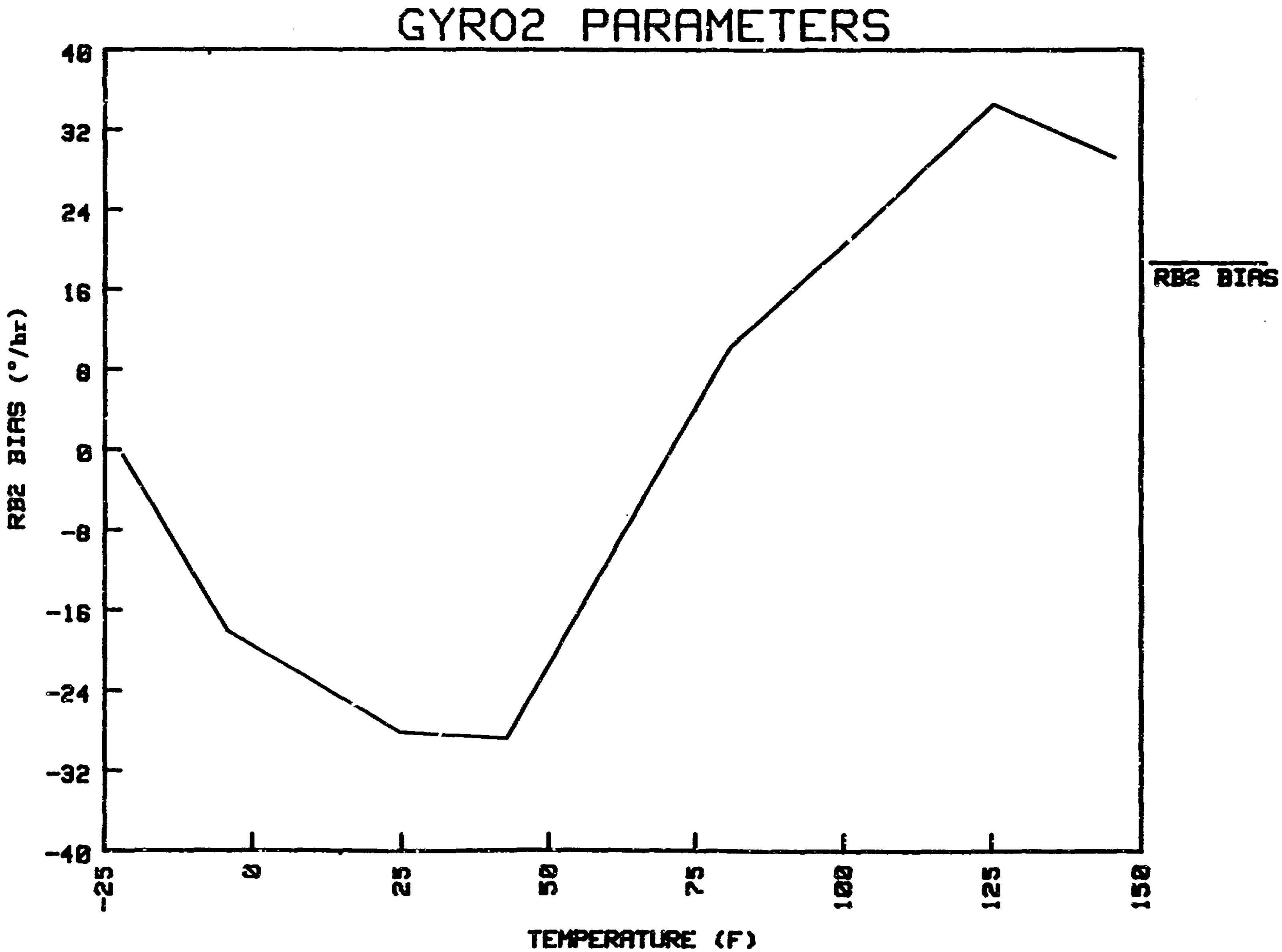

Figure 14. Gyro 2 bias drift/temperature (RB2).

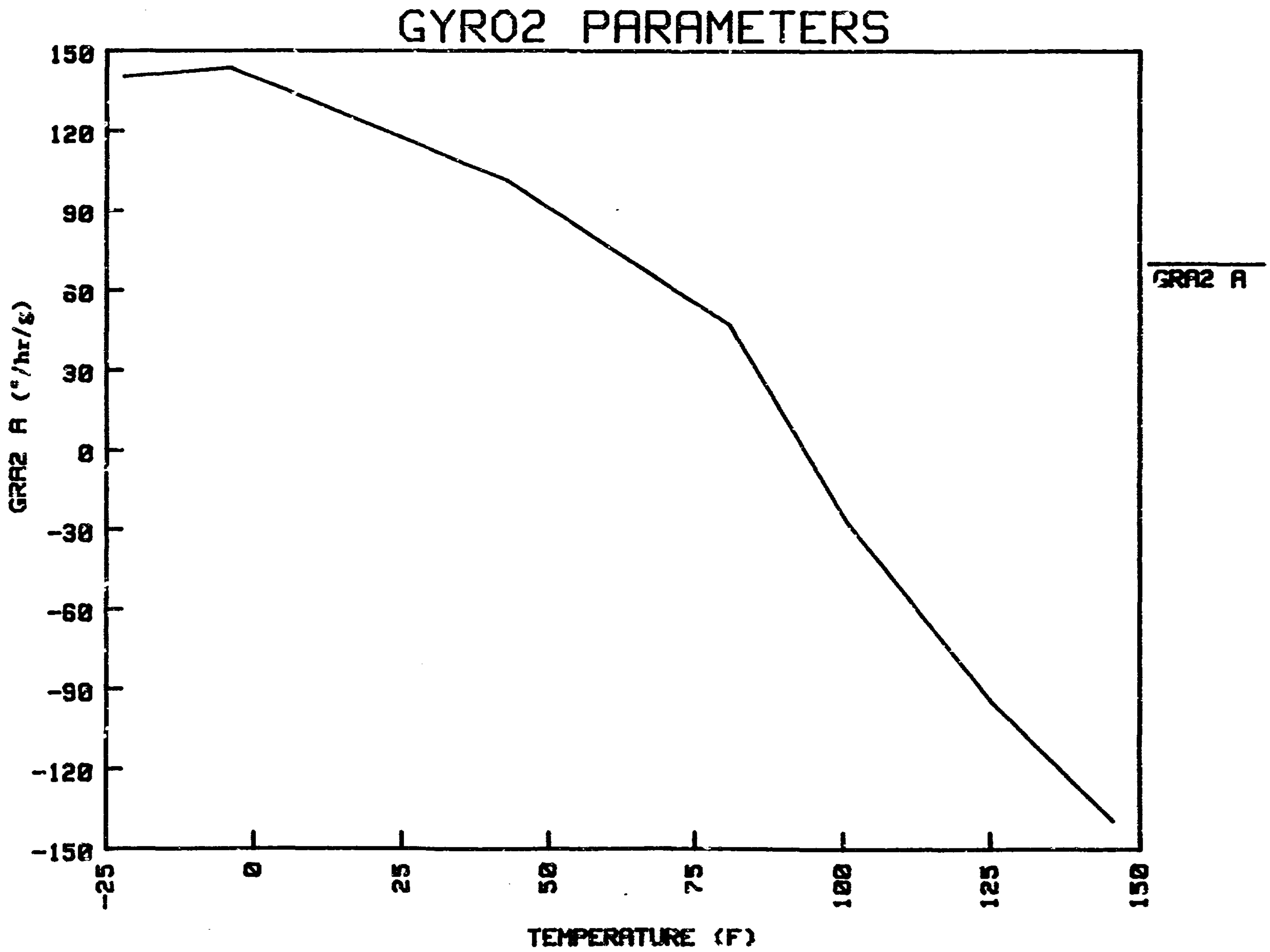

Figure 15. Gyro 2 g-sensitive drift/temperature (GRA2A).

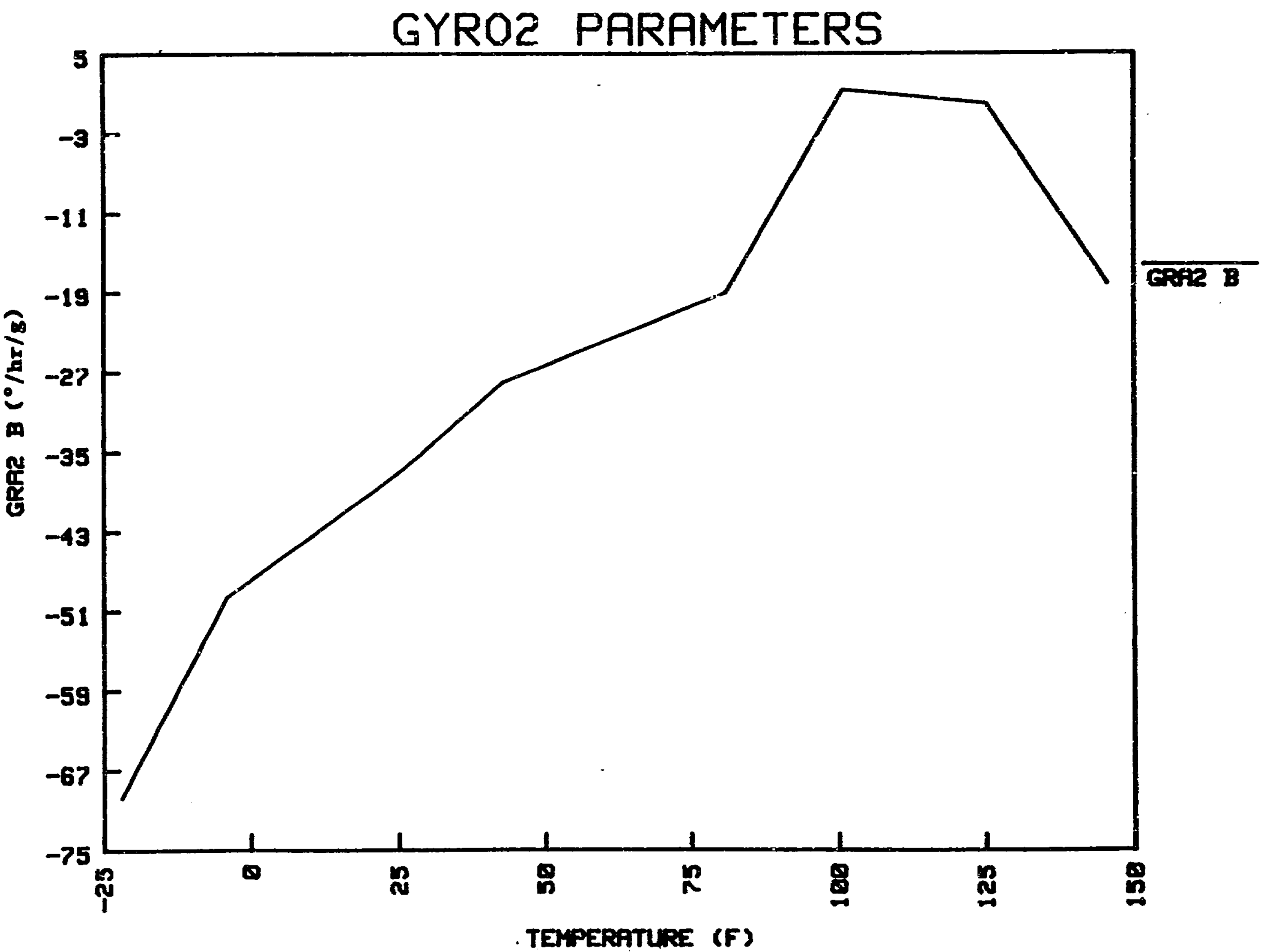

Figure 16. Gyro 2 g-sensitive drift/temperature (GRA2B).

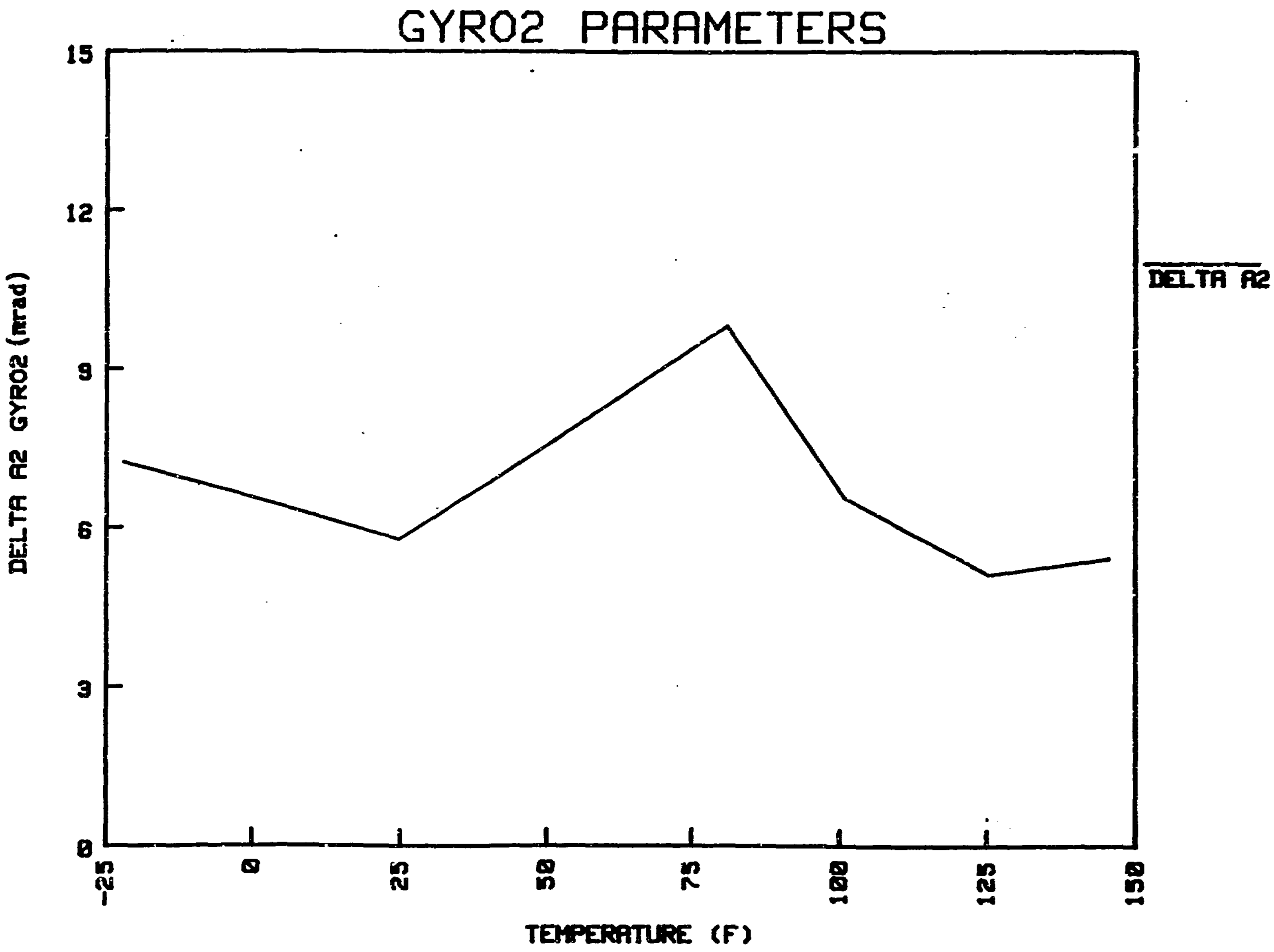

Figure 17. Gyro 2 misalignment error.

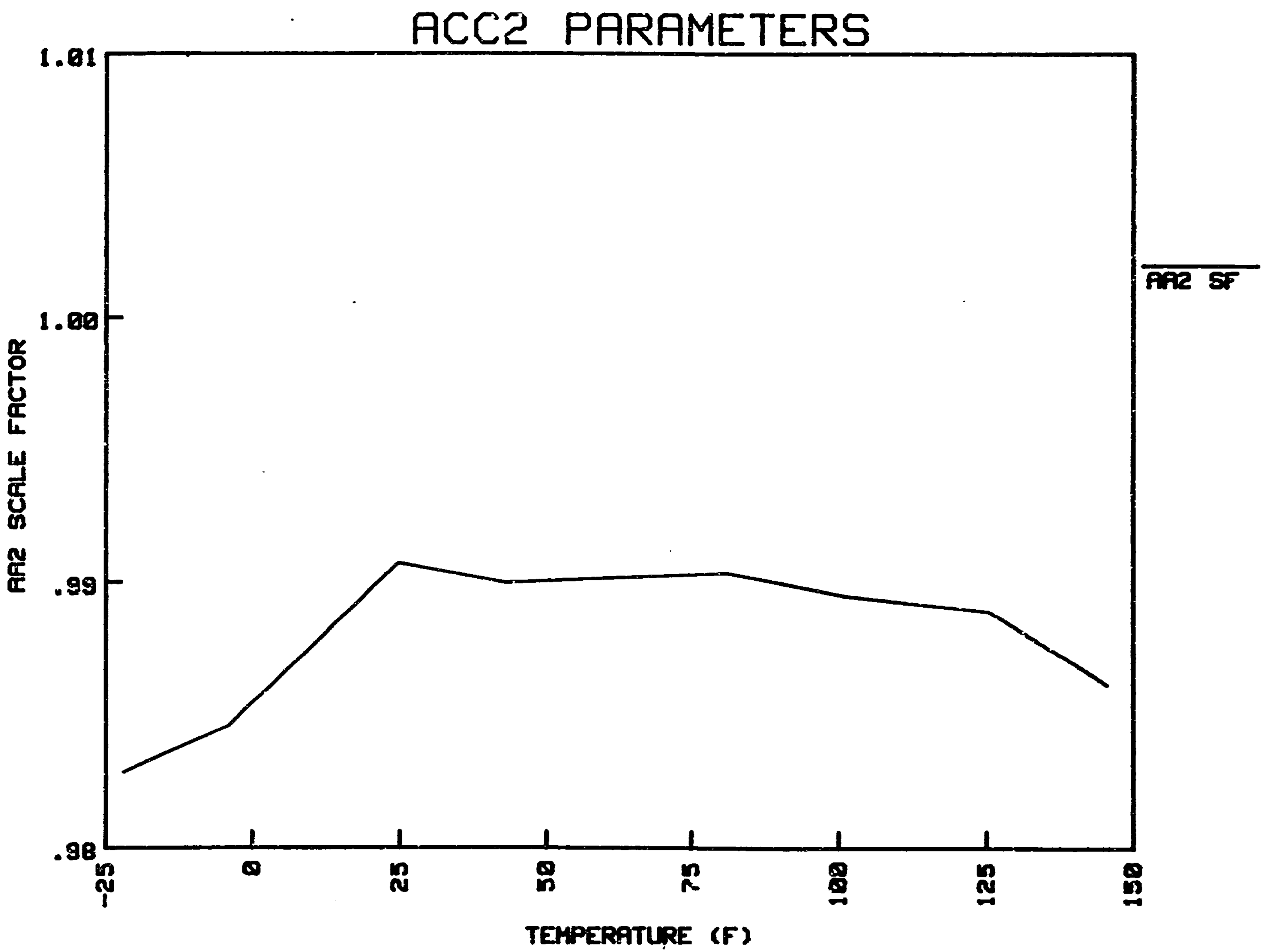

Figure 18. Accelerometer 2 scale factor/temperature.

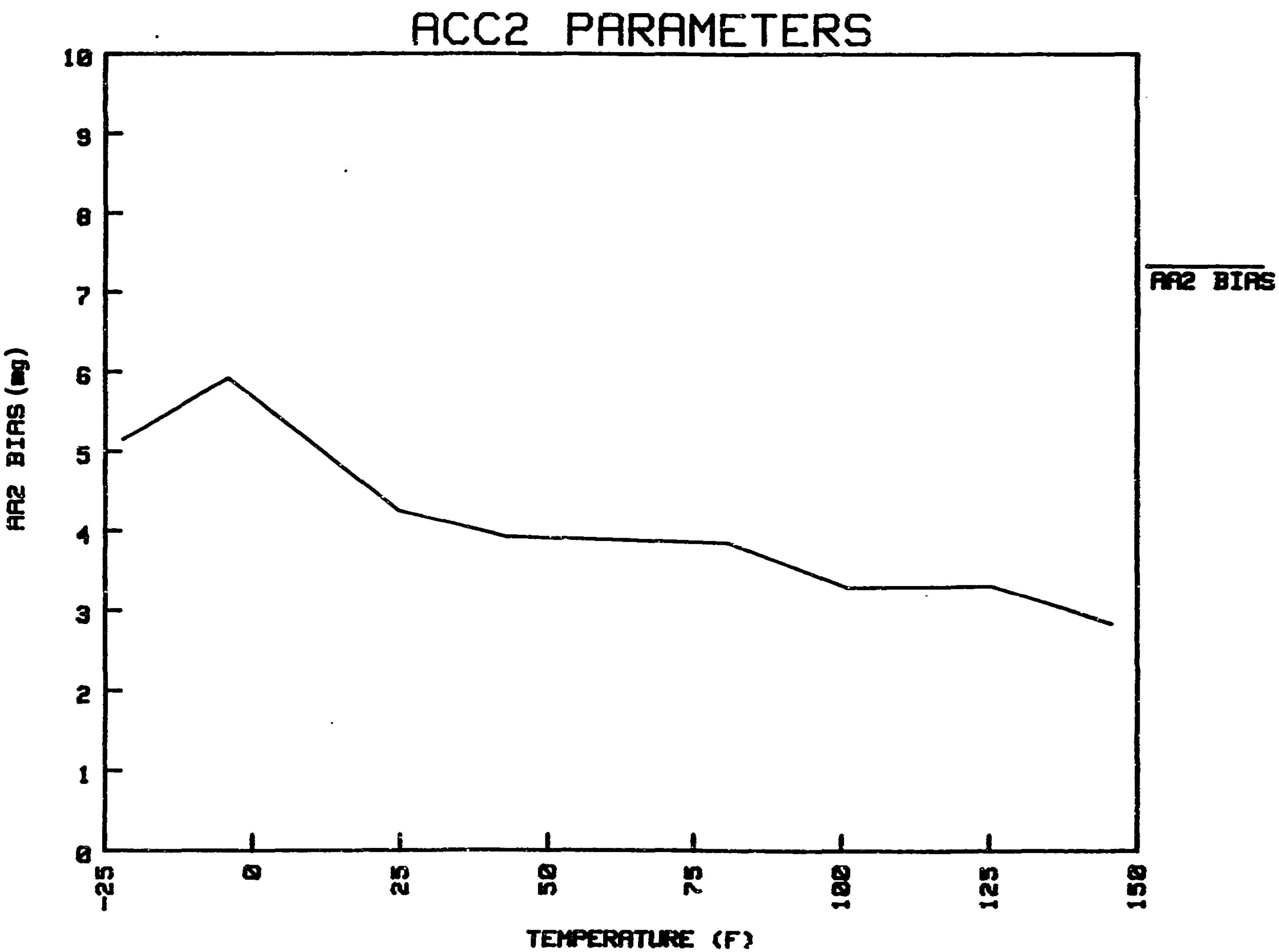

Figure 19. Accelerometer 2 bias/temperature (AA2).

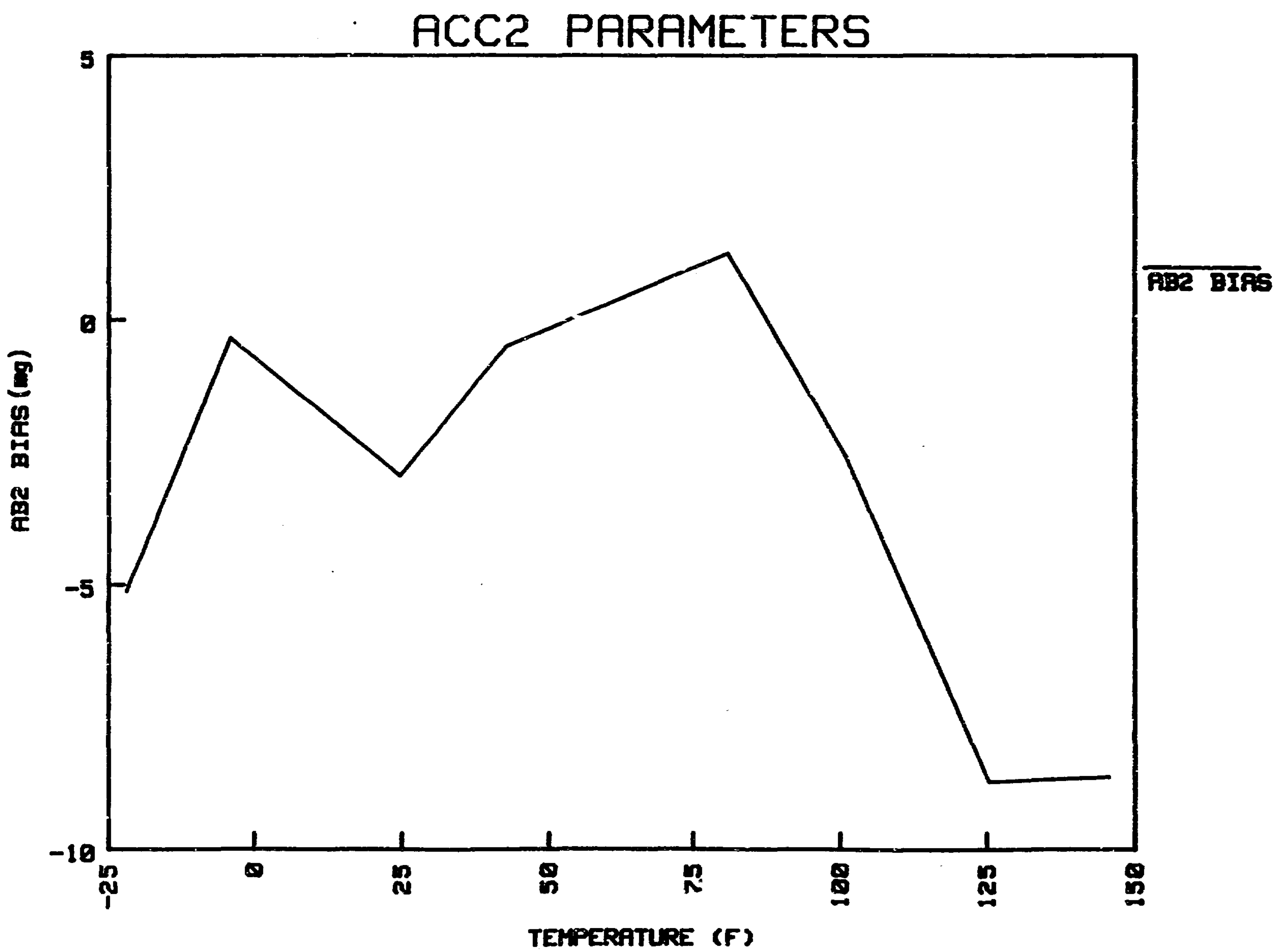

Figure 20. Accelerometer 2 bias/temperature (AB2).

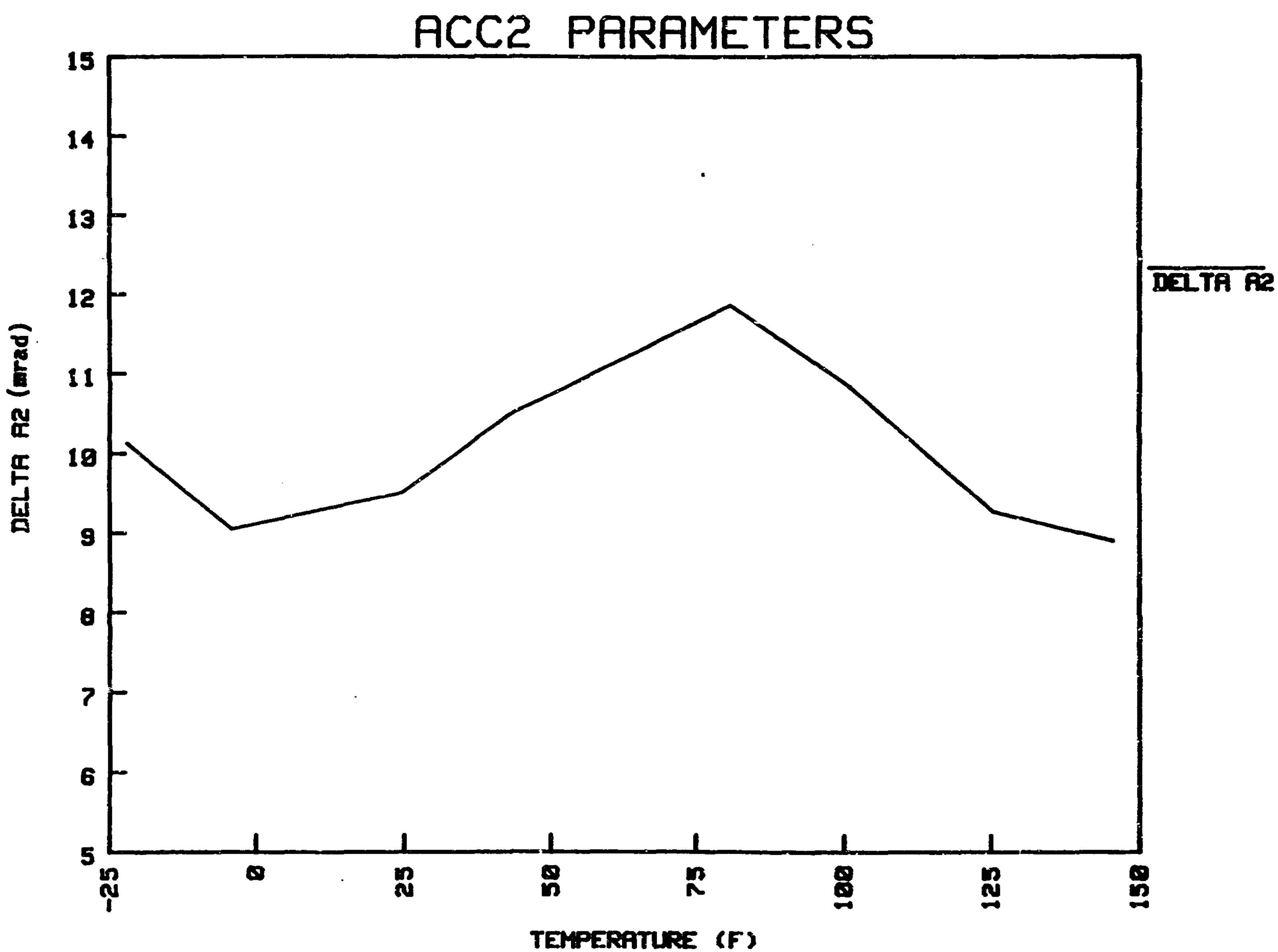

Figure 21. Accelerometer 2 misalignment error.

VI. CONCLUSIONS

Improvements are needed in the performance stability of the 958T-2 sensors. The residual scale factor errors after thermal compensation are shown in Figures 2 and 12. Table 1 summarizes the randomness of the scale factor. Note that the variations of the scale factor exhibit an uncertainty of 795 to 2006 PPM. These variations show the need for scale factor accuracy improvement for certain IMU applications. One error mechanism causing uncertainties is the temperature dependent mechanical stress across the support bearings. These stresses are also known to be a major source of bias variation (see Figs. 3, 4, 9, and 10).

It is also known that piezoelectric transducers are limited in scale factor accuracy due to aging and temperature sensing errors. From the literature on these transducers it is recognized that they exhibit a long term aging characteristic of 2000 to 5000 PPM over a period of several years. However, there are other transducer materials that may be applicable to the multisensor concept. One possibility is the piezo-resistive silicon strain sensing transducers. These have well known stability characteristics.

Improvements in sensor performance stability are needed to satisfy a viable software polynomial thermal compensation scheme. It appears that a stable sensor concept would be the most cost-effective thermal compensation technique, if sensor improvements are achievable. The results of this evaluation show the need to reduce scale factor and bias randomness including temperature dependent g-sensitive gyro drift, other temperature sensitive drifts and repeatability errors due to internal structural stresses. The results also show the need to improve the performance of electronics used to amplify, process, demodulate and convert inertial signals to digital pulses with high resolution.

The Collins Phase III self-calibration unit is not an acceptable design because the self-calibration time is approximately 4 minutes and the gimbal torque motors require excessive power. However, if the concept of gimbal self calibration becomes a serious candidate for a built-in-test calibration capability, further work is required to satisfy a viable design.

VII. RECOMMENDATIONS

- Continue research for 1 year to develop better sensors.
- Explore quick reaction gimbal mechanisms which require very little power.
- Build two designs: one concept using software thermal compensation and the other utilizing prelaunch self calibration.
- Decide the merit of the two designs.

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